Evaluation of Tunnel Concepts for Advanced Aviation Displays

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Eight 757 commercial airline captains flew 22 approaches using the Reno Sparks 16R Visual Arrival simulated Cat IIIa conditions. Approaches were flown using a synthetic vision display that was chosen as an advanced aviation display to evaluate four tunnel or pathway concepts and compared their efficacy to a baseline condition without a tunnel. Two new "dynamic" tunnel concepts were developed and evaluated in addition to both a minimal and box tunnel concept. The results showed that the tunnel concepts significantly improved pilot performance and situation awareness and lowered workload compared to the baseline condition. The dynamic tunnel concepts were found to be the best candidates for advanced aviation displays. These results are discussed with implications for display design and future research.

Keywords: Synthetic Vision; Situation Awareness; Pathway Displays; Tunnel Displays; Highway-In-The-Sky

INTRODUCTION

Our society is highly dependent on air transportation. In the relatively short span of 100 years, we have progressed from flights of a few hundred feet to routine trips over oceans to distant parts of the world. Speed, altitude, and range all have increased a thousand-fold since that early December morning in 1903. As Leonardo da Vinci observed, "A bird is an instrument working according to mathematical law, which instrument is within the capacity of man to reproduce in its movements." Today, that dream has been realized. The sky is no longer the limit. Now, a new problem visits us. If air traffic demands does triple as predicted within the next 20 years, the relatively low accident rate of less than 2 accidents per million flights will become unacceptable (NASA, 2001). Dramatic steps, therefore, are needed to ensure the unquestioned safety for the traveling public that has made flying the safest mode of transportation.

The NASA Aviation Safety Program (AvSP), at NASA Langley Research Center, has taken on the challenge to "develop and demonstrate technologies that contribute to a reduction in the aviation fatal accident rate by a factor of 5 by year 2007" (NASA, 2001). This NASA Aerospace Technology Enterprise goal will be a difficult one to meet, and joint FAA and NASA research has been focused on several new technologies that together will help make it a reality.

NASA Synthetic Vision System

To help meet national aviation safety goals will require mitigating or eliminating the etiologies of accidents. A significant factor involved in many commercial and general aviation accidents is limited visibility. The ability of a pilot to ascertain critical information through visual perception of the outside environment can be limited by various weather phenomena, such as rain, fog, and snow. Since the beginning of flight, the aviation industry has developed various devices to overcome these low-visibility limitations. These include attitude indicators, navigation aids, Instrument Landing Systems (ILS), moving map displays, and Terrain Awareness Warning Systems (TAWS). All of the aircraft information display concepts developed to date, however, still require the pilot to continuously perform information acquisition and decoding to update and maintain their mental model in order to "stay ahead" of the aircraft when outside visibility is reduced. What this means is that pilots still have to interpret the "coded" (Theunissen, 1997) information and match it to the outside world.

AvSP initiated a new research project to develop technologies to help overcome safety problems associated with limited visibility. The NASA Synthetic Vision System (SVS) project is based on the premise that better pilot situation awareness during low visibility conditions can be achieved by reducing the steps required to build a mental model from disparate pieces of data through the presentation of how the outside world would look to the pilot if their visibility were not restricted. New technological developments in navigation performance, low-cost attitude and heading reference systems, computational capabilities, and graphical displays allow for the prospect of SVS displays for virtually all aircraft classes. SVS display concepts employ computer-generated terrain imagery, on-board databases, and precise position and navigational accuracy to create a three dimensional perspective presentation of the outside world, with necessary and sufficient information and realism, to enable operations equivalent to those of a bright, clear, sunny day regardless of the outside weather condition. The SVS concept includes the intuitive display of intended flight path by tunnel or pathway-in-the-sky presentations. When coupled with a synthetic view of the world, the spatially integrated depiction of the intended aircraft flight path and its relation to the world provides an intuitive, easily interpretable display of flight-critical information for the pilot. The safety outcome of SVS is a display that should help reduce, or even prevent, controlled-flight-into-terrain (CFIT), which is the single greatest contributing factor to fatal worldwide airline and general aviation accidents (Boeing, 1996; Prinzel et al., 2002; 2003; in press). Other safety benefits include reduced runway incursions and loss-of-control accidents (Williams et al., 2001) in addition to significant economic benefits (Hemm, 2000).

Advanced Pathway Displays

Although avionics have advanced significantly since Jimmy Doolittle flew the first "blind" flight in 1929, Theunissen (1997) noted that significant increases in aviation safety are unlikely to come by extrapolating from current display concepts. He further stated that, "new functionality and new technology cannot simply be layered onto previous design concepts, because the current system complexities are already too high. Better human-machine interfaces require a fundamentally new approach" (1997; p.7). Bennet and Flach (1994) argued that such an approach should not focus on development of "idiot-proof" systems because of the infinite potential problem space, but rather should provide the pilot information that would enable successful solution sets to be generated. These displays should present continuous information about spatial constraints rather than command changes to reduce error states, and should show error margins that depict the bounds that the pilot may safety operate in contrast to the compensatory control strategy required by current cockpit instruments. This can be accomplished through the use of "pathway" or "tunnel" displays. Several NASA projects, including SVS, are exploring the use of flight path depiction as key parts of the human-computer interface. Therefore, there is significant need and importance for research conducted toward tunnel concepts usable as part of these advanced aviation displays.

A considerable body of research exists demonstrating the effectiveness of pathway displays for horizontal and vertical guidance and enhancing situation awareness (e.g., Haskell & Wickens, 1993; Williams, 2002). Many of these studies, however, failed to emulate the flight conditions that tunnel displays are postulated to ameliorate (e.g., curved approaches). Rather, often they are conducted using part-task simulations under conditions of low workload (e.g., straight-in approaches). Moreover, the tunnels were presented alone supplemented only by minimal flight instrumentation. Therefore, little evidence is available to guide design for complex graphical displays, such as synthetic vision, when the tunnel interacts with other primary flight symbologies and graphical presentation.

Research Objective

The objective of the present study was to examine several tunnel concepts that have been investigated in past research to determine their efficacy for synthetic vision displays. Synthetic vision was chosen because it represents arguably the most complex graphical display currently being developed and, therefore, any research findings may better generalize to other advanced aviation displays. In addition, two new pathways were conceptualized and evaluated that theoretically represented the best combination of current tunnel formats. Together, four tunnel (box tunnel, minimal "crows feet", dynamic "crows feet", dynamic pathway) and baseline concepts were evaluated. Eight B-757 current major airline Captains flew the Reno, NV Sparks 16R visual arrival, curved approach under CAT IIIa instrument meteorological conditions (IMC); an approach of significant workload and difficulty under such conditions. The scenarios were chosen to best evaluate the four tunnel concepts, as part of the SVS display, under situations posited for a future commercial concept of operation for synthetic vision.

METHOD

Pilot Participants

Eight commercial pilots (ATP), who fly for major commercial airlines, participated in the experiment. All participants were HUD-qualified and were rated B-757 Captains. The HUD requirement was to ensure familiarity with a velocity vector and guidance symbology. All participants also had logged flight time in "glass cockpits" (e.g., A-320; MD-11) other than the B-757; therefore, all participants were familiar with a primary flight display (PFD).

Tunnel Concepts

Four tunnel (box, minimal, dynamic “crow’s feet”, dynamic pathway) and baseline (i.e., no tunnel) concepts were evaluated (see Figure 1). The "box" tunnel, a concept that is the subject of most of the tunnel research in the literature, consisted of a series of boxes connected at the corners to form a path within which the pilot flies. It was presented out to a length of 10 nm, with no fading. The minimal tunnel concept consisted of a series of "crows feet" presented in each corner of a tunnel segment (essentially a truncated box). The tunnel presentation was 5 tunnel segments per nautical mile (nm) with a total length of 3 nm, and faded gradually to invisibility over the last nautical mile. The third concept, dynamic "crows feet", allowed the "crows feet" to grow as a function of path error. Therefore, the pilots are given feedback as to where they are in the tunnel and if they are close to flying out of the tunnel. The idea of the dynamic tunnel was that if the pilot is flying in the center of the tunnel, there should be the smallest amount of clutter. However, if there exists appreciable path error, the tunnel walls would "grow" to help the pilot gauge where the boundaries of the tunnel are. This helps to overcome a frequent criticism of "low clutter" tunnels. The fourth concept, dynamic pathway, was a variation of the dynamic "crow’s feet" concept in which the floor of the tunnel was presented at all times. For both the dynamic pathway and dynamic “crow’s feet”, when the pilot left the tunnel, the tunnel would change to a “trough” and resemble a box tunnel with the exception that the tunnel would open to “invite” the pilot back into the tunnel. All concepts and the baseline were paired with a navigation display with a Terrain Awareness Warning System (TAWS).

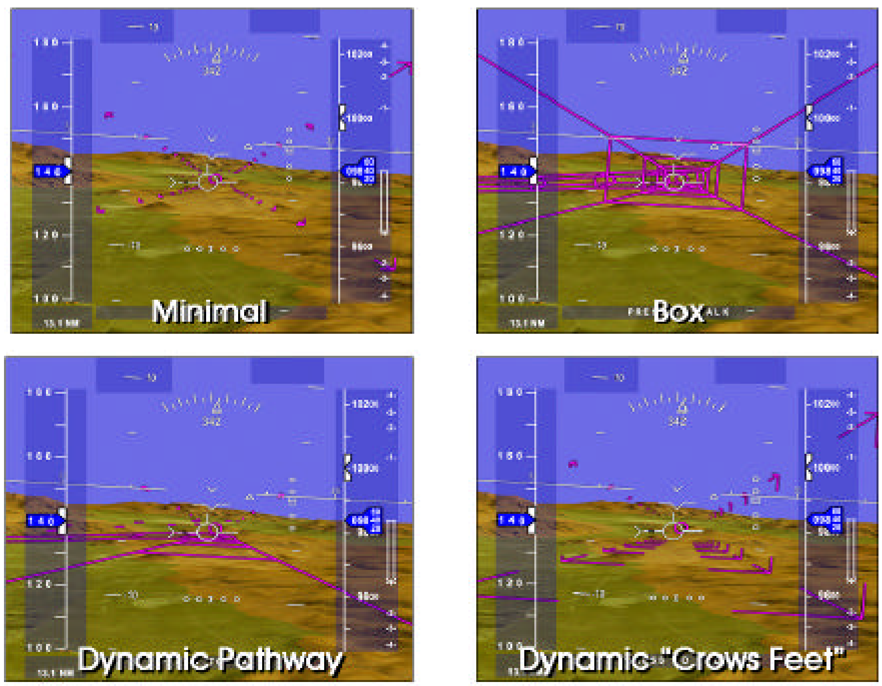

Figure 1. Four Tunnel Concepts

Experimental Task

Pilot participants were required to fly the Sparks Visual Arrival to Runway 16 at Reno airport (RNO). Twenty-two experimental runs were completed during the experimental session. The runs differed from each on the (1) initial starting position outside the tunnel, (2) the guidance symbology, and (3) task scenario. There were three initial starting positions that were randomly varied across trials to force the pilot to re-enter the tunnel on each run. The guidance symbology was also randomly assigned and factorially combined with the four tunnel concepts. However, these results are not discussed here and the results are confined only to the flight director “ball” that is standard on many current aviation displays. Finally, there were two scenarios required of the pilot participants. The first was the nominal Sparks 16R Visual Approach, but flown under IMC, and the second was a “cut-the-corner” scenario in which the pilot was instructed by Air Traffic Control (ATC) to leave the tunnel and fly “direct to” the McRAN waypoint 90 degrees opposite the KNB16 FMS waypoint. The latter scenario required the pilot to utilize the navigation display (i.e., using the predictor noodle to acquire the heading) and later to use the guidance symbology and velocity vector to re-enter the tunnel at the McRAN waypoint. Afterward, the pilot was cleared to continue the approach and land on runway 16R.

Simulation Facility

The experiment was conducted in the Visual Imaging Simulator for Transport Aircraft Systems (VISTAS) III simulator at NASA Langley Research Center. The single pilot fixed based simulator consists of a 144° by 30° Out-The-Window (OTW) scene, a simulated HUD, a large feld head-down display (HDD) and pilot input controls. The OTW scene was used only during training. The pilot controls in the VISTAS III workstation are a left side arm controller, left/right throttle controls, rudder pedals, toe brakes, a PC track ball for display-related pilot inputs, and a voice recognition system (VRS). The VRS is a speaker-independent voice recognition system that provided a robust, rapidly reconfigurable pilot-vehicle interface. It was also used to provide automated alerts, warnings, and simulated ATC commands. The aircraft model was a B-757, and both the approach and departure speed targets were 138 knots. All scenarios were flown with moderate turbulence. Auto throttles were used, flaps were set to 30 degrees, and the landing gear was down.

RESULTS

After each run, pilots were administered a run questionnaire consisting of the USAF Revised Workload Estimation Scale (Ames & George, 1993), Situation Awareness Rating Technique (SART) (Taylor, 1990), and six Likert-type (7-point) questions specific to tunnel evaluation. Simple ANOVAs and Student-Newman-Keuls post-hoc tests were performed. Alpha was set at .05.

Mental Workload

There was a significant effect found for tunnel with respect to workload, $F(4,28) = 43.40$. The baseline condition (4.167) was rated significantly higher in workload than the four tunnel concepts. The minimal tunnel (3.167) was also rated significantly higher in workload than the box (2.583), dynamic pathway (2.542), and dynamic “crow’s feet” (2.417), which did not differ from each other.

Situation Awareness

There was a significant effect found for tunnel with respect to the combined SART ratings, $F(4,28) = 11.41$. The no tunnel, baseline condition (3.417) was rated significantly lower in situation awareness (SA) than the four tunnel conditions. In addition, the minimal tunnel concept (5.083) was rated significantly lower than the box (7.167), dynamic pathway (7.458), and dynamic “crows feet” (7.542) which did not differ from each other.

Run Questionnaire

There was a significant effect found for several run questions asked. First, there was a significant effort found for SA, (“As I performed the task, my awareness of where I was in the tunnel was ___.”), $F(3,21) = 22.07$. The minimal tunnel (2.833) was rated significantly lower in SA than the three other tunnel concepts. The dynamic pathway (5.00) was also rated significantly lower than the box (5.9167) and dynamic “crows feet” (6.0417), which did not differ from each other.

A second SA question asked concerned, “As I performed the task, my awareness of upcoming turns was ___.” An ANOVA found a significant effect for tunnel, $F(2,21) = 5.06$. The minimal tunnel concept (3.292) was rated significantly lower than the dynamic “crow’s feet” (5.208), dynamic pathway (5.208) and box (5.542) tunnel concepts.

A third question asked, “As I performed the task, my level of flight path control and performance was ____.” A significant effect was found for display concepts (including baseline), $F(4,28) = 27.05$. The baseline condition (3.583) was rated significantly lower than the four tunnel concepts, which did not differ from each other.

A final question for tunnel evaluation was, “As I performed the task, my ability to intercept the path and re-enter the tunnel was ___”. A significant effect was found for tunnel, $F(3,21) = 17.54$. Participants rated the minimal tunnel concept (3.667) significantly lower than the box dynamic pathway (5.083), dynamic “crow’s feet” (5.333), and box tunnel (5.333) concepts. The three tunnel concepts were not statistically different from each other.

Flight Path Control

Flight path control was analyzed for the nominal task run for root-mean-squared error (RMSE). Because guidance symbology may confound flight path accuracy, the results were analyzed as symbology-tunnel combinations yielding six display concepts plus the baseline (i.e., no tunnel, ball symbology). An ANOVA found a significant effect for lateral RMSE across guidance symbology-tunnel combinations, $F(6,42) = 6.839$ (Figure 2). The baseline condition was found to be significantly worse for lateral flight path control (132.63 feet). No statistical differences were found for lateral RMSE between the three tunnel concepts regardless of the guidance symbology. No significant differences were found for vertical path error across the display concepts including the baseline condition ($\underline{p} > .05$).

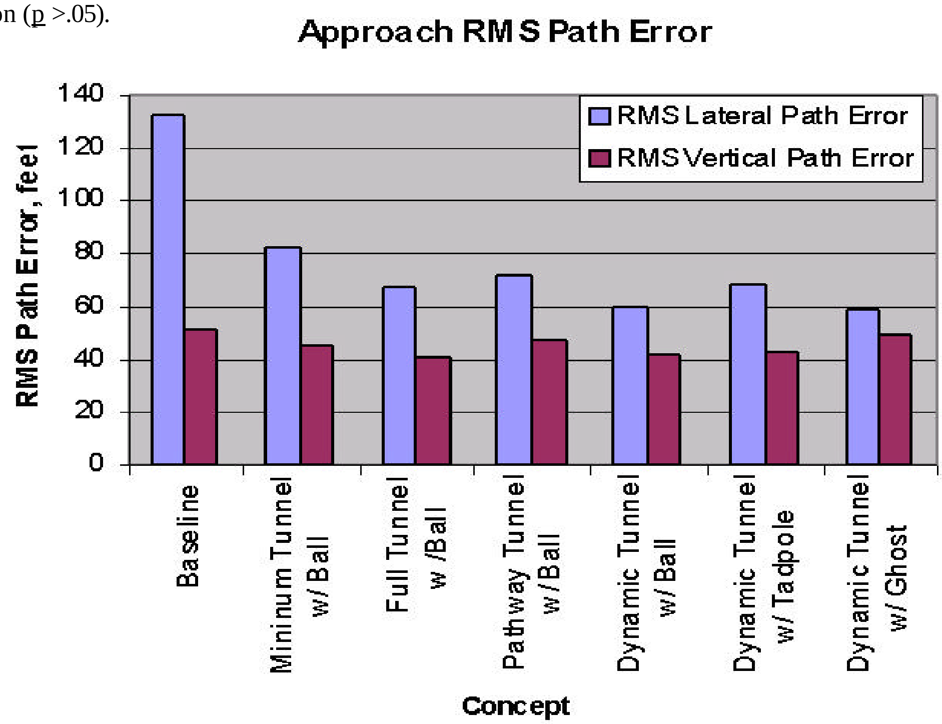

Figure 2. Approach RMS Path Error

Semi-Structured Interview

A semi-structured interview was conducted after the final experimental run. A number of Likert (1 to 7) questions were asked but space does not allow a detailed summary of the results. However, several interesting results were found. For example, although there was no significant difference in rating for effectiveness of tunnels for straight path segments, pilots rated the minimal tunnel concept (4.00) significantly less effective for curved path segments than the box (5.4), dynamic pathway (6.2), and dynamic “crows feet” (6.4), $F(3,28) = 10.09$.

Another interesting finding was that pilots rated the baseline (5.6) and minimal tunnel (4.5) concepts to have significantly more workload to intercept the path during the “cut-the-corner” scenario, $F(3,35) = 43.56$. There were no statistical differences between the box (3.0), dynamic pathway (1.9) and dynamic “crows feet” (1.8) concepts.

SA-SWORD

Overall, pilots ranked the dynamic “crow’s feet” first in overall preference followed by dynamic pathway, box, and minimal tunnel. A distant fifth was the baseline condition which several pilots noted after flying the tunnel displays remarking, “how am I ever to go back to an EADI [electronic attitude direction indicator] after flying these displays?” An analysis of the results from the Situation Awareness Workload Dominance Scale (SA-SWORD (Vidulich & Hughes, 1991) confirmed this ranking. An ANOVA found a significant effect for tunnel, $F(4, 28)=84.369$ for the SA-SWORD paired comparison measure. Post hoc tests showed 4 distinct subgroups formed:

1) Dynamic; 2) Pathway; 3) Full and Minimum; and 4) Baseline. The Dynamic tunnel was ranked as having the greatest SA and Baseline (no tunnel) the worst. The ranking from highest SA to lowest was: Dynamic tunnel, pathway tunnel, full tunnel, minimum tunnel and baseline (no tunnel).

DISCUSSION

The results of the study indicated that all the tunnel concepts were better than having no tunnel at all. However, the minimal tunnel was found to be the least effective of the tunnel concepts in general. Although the "box" tunnel was effective, it had significant limitations in terms of excessive clutter while inside the tunnel. The dynamic pathway and dynamic "crows feet" tunnel concepts were the most effective, and were judged to be superior and similar in terms of situation awareness and workload. However, overall, the dynamic "crow's feet" tunnel was ranked the highest and is the recommended tunnel concept for future synthetic vision displays. These results can also be generalized to other advanced graphical aviation displays. Research is currently being conducted with head-up (Figure 3) and full-color, stereoscopic helmet-mounted displays to further evaluate these results.

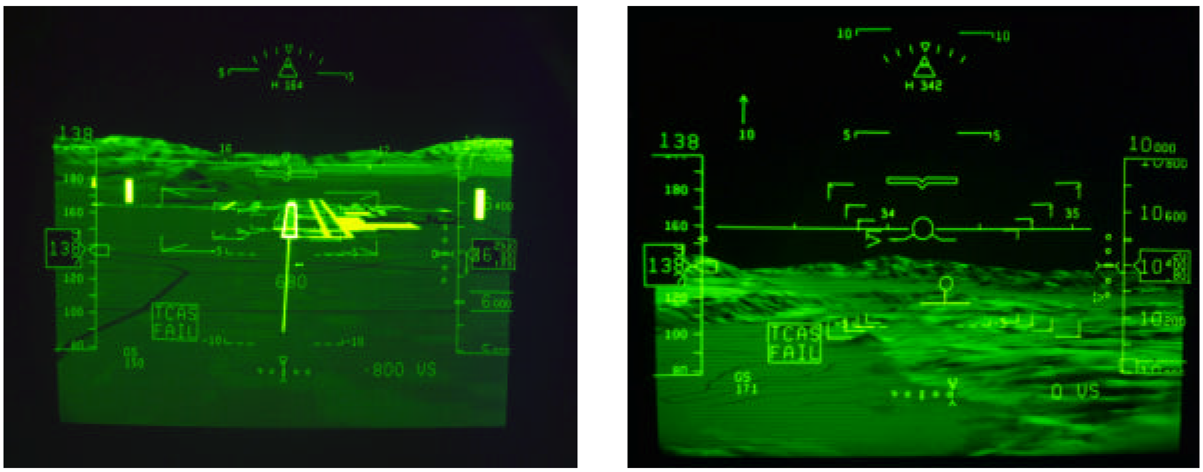

Figure 3. NASA Synthetic Vision Head-Up Display

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